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Original Research Paper

Modeling filtration performance of elliptical fibers with random distributions

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ABSTRACT

The fibrous media with elliptical cross sections may improve the filtration performance, however, current researches mainly focus on the capture mechanisms of a single elliptical fiber, and the fibrous media with randomly distributed fibers are rarely involved. In this work, a 2D numerical model was developed to predict the pressure drop and particle penetration for the fibrous filter composed of randomly distributed elliptical fibers. The results show that a big solid volume fraction of filter increases the effective collision area, and enhances the capture at a low face velocity. The particle penetrations through the fibers with the diameter of 5 μm are conspicuously weaker than those with the diameter of 10 μm, especially at big solid volume fractions and high face velocities. The blunt elliptical fibers restrain the penetration more effectively than the circle ones when the solid volume fraction is high. Though the blunt fibers lead to a large drag force, the increased pressure drop cannot improve the filtration performance at low solid volume fractions. In most cases, the slim elliptical fibers can enhance the filtration performance. A bigger aspect ratio of elliptical fibers leads to a low quality factor, showing the capture efficiency increases with the penalty of a high pressure drop.

1. Introduction

The severe particulate pollution in the indoor or outdoor environment has posed a significant threat to human health. As an effective way to remove the particles from air, fibrous filters have gained growing attentions in recent years. Schroën et al. [1] summarized the current advances of particle movement in laminar shear fields which is regarded as a new starting point for the large scale separation technology. Wang et al. [2] investigated the effect of high voltage on the filtration performance of carbon fabric filters. Moreover, a lot of empirical expressions have been developed to calculate the pressure drop and particle penetration percentage of the fibrous media [3–12]. It should be noted that the aforementioned studies mainly focus on the circular fibers. However, more and more non-circular fibers, like the elliptical, trilobal and square or rectangular form, are widely used, which have been proved to perform better than the traditional circular fibers [13–18]. Among these non-circular candidates, the elliptical fiber is more streamlined, which may result in a lower drag force [19]. Besides, the specific area per unit volume of elliptical fiber is bigger than the circular one, thus the elliptical fiber performs well for the submicron particles [20]. Although the elliptical fibers have some potential advantages, the related investigations are relatively limited. Brown [21] predicted the air flow field and pressure drop of a bundle of elliptical fibers with a regular arrangement. Raynor [22] investigated the interception efficiency of elliptical fibers for various scenarios, concluding that the single fiber interception efficiency increases with increasing the particle diameter and aspect ratio. Based on the simulation results, Regan and Raynor [23] proposed an expression to calculate the diffusion efficiency of elliptical fibers, and found that the Peclet number had a clear impact on the diffusion efficiency. Raynor and Kim [24] numerically investigated the filtration characteristics of trilobal and elliptical fibers, finding that the elliptical fibers are more valid to remove small particles. The numerical simulations by Wang and Pui [25] showed that the blunt elliptical fibers have a better performance for the particles dominated by interception and impaction, while the slim fibers are more suitable for the particles controlled by diffusion mechanism. For the nanoparticles, Kirsh [26] calculated the Stokes flow field around a bundle of elliptical fibers and obtained the relationship of the fiber capture coefficient with the Peclet number. Using the Zhukovsky conversion, Wang et al. [27] calculated the

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Nomenclature

AR	aspect ratio (–)
C	normalized particle concentration (–)
C_c	Cunningham correction factor (–)
D	diffusion coefficient (m^2/s)
d_f	fiber diameter (μm)
d_p	particle diameter (μm)
E	total collection efficiency of a single fiber (–)
E_D	single fiber capture efficiency induced by Brownian diffusion (–)
E_I	single fiber capture efficiency induced by impaction (–)
E_R	single fiber capture efficiency induced by interception (–)
ΔF	increased filtration percentage (–)
f_c	filtration per thickness for the circular fibers (m^{-1})
f_e	filtration per thickness for the elliptical fibers (m^{-1})
G_i	random number (–)
J	empirical coefficient (–)
Kn	Knudsen number (–)
Ku	Kuwabara factor (–)
$n(t)$	Brownian force (N)
P	penetration percentage through fibrous media (–)
Δp	pressure difference (Pa)
Pe	Peclet number (–)
Q	quality factor (–)
R	ratio of particle diameter to fiber diameter (–)
Stk	Stokes number (–)
SVF	solid volume fraction (–)
T	temperature (K)
t	thickness of filter media (μm)
U	face velocity (m/s)
u_p	particle velocity (m/s)
u, v	velocity components (m/s)
x	x coordinate
y	y coordinate

Greek symbols

σ	Boltzmann constant (J/K)
λ	mean free path of air (m)
v	kinetic viscosity (m^2/s)
μ	dynamic viscosity ($N\ s/m^2$)
ρ_p	particle density (kg/m^3)

flow field near a single elliptical fiber, concluding that the elliptical fiber can significantly enhance the interceptive efficiency. Wang et al. [28] used a lattice Boltzmann-cellular automata model to simulate the pressure drop and filtration efficiency of an elliptical fiber, finding that the elliptical fiber performance is closely related to the aspect ratio and orientation.

From the aforementioned studies, it can be seen that the capture mechanisms of the single elliptical fiber were intensively clarified, but the elliptical fiber bundles were rarely involved. Even if the fiber bundles are studied, most fibers are regularly arranged. However, the fibers in the real filter are randomly distributed, so the current researches can't accurately predict the filtration performance of elliptical fibers. In order to simulate the disordered arrangement, Hosseini and Tafreshi [29] adopted an algorithm to generate the random structure inside fibrous media, which can accurately predict the filtration characteristics of filters. The randomly distributed fibers were then used to predict the pressure drop and capture efficiency. Whereas these investigations paid more attentions on circular fibers, few upon elliptical ones. In this work, the pressure drop and filtration characteristics of the elliptical fibers with a random arrangement will be investigated, which can contribute to the filtration performance improvement of filters in practical engineering.

2. Flow model

Inside the fibrous media, the air follows the Stokes flow. The continuity and momentum governing equations are listed below [29], for which the inertial effects are ignored:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \tag{1}$$

$$\frac{\partial p}{\partial x}=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial p}{\partial y}=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

The commercial CFD software FLUENT is used to solve the Eqs. (1)(3) and the fluid density and viscosity at the room temperature are employed. For generating a 2D geometry with an irregular fiber arrangement, the coordinates of the ellipse center should be first calculated by a random algorithm in MATLAB, and then the major and minor axes are created by moving the center. These coordinate data are imported to the mesh software Gambit via a script file. Finally, the randomly distributed fibers are obtained by connecting the characteristic points to an ellipse. In this study, the overlaps between fibers are ignored to improve the mesh quality, and the minimum distance between two fibers is restricted to be $0.05d_f$, where d_f is the equivalent fiber diameter. The elliptical fibers have the same area as the circular counterparts, yet, different perimeters. Fig. 1 shows the 2D geometry of the fibrous media composed of elliptical fibers with d_f = 5 μm and solid volume fraction (SVF) of 10%.

As shown in Fig. 1, the inlet of the computational domain is set as a velocity inlet and a pressure boundary condition is applied to the outlet. The lateral surfaces of the domain are symmetric. The inlet and outlet boundaries are placed respectively $20d_f$ and $5d_f$

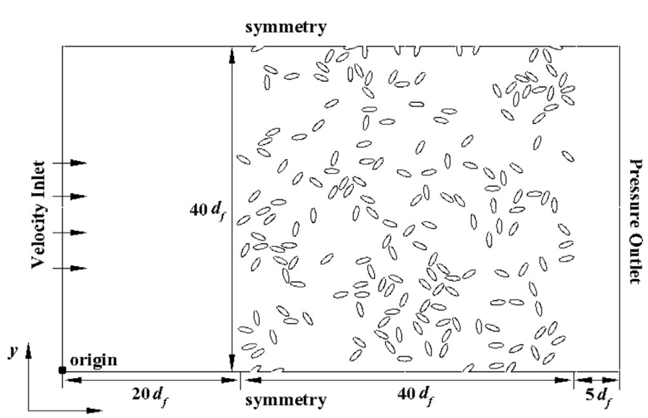

Fig. 1. Boundary conditions and geometries of fibrous media composed of slim elliptical fibers with d_f = 5 μm and SVF = 10%.